Ekman Volume Fluxes for the World Ocean and Individual Ocean Basins

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ABSTRACT

Monthly climatological estimates of wind stress have been used to compute Ekman volume fluxes in the world ocean. Specifically, meridional and zonal Ekman volume fluxes have been computed and from the divergence of these horizontal components, the vertical Ekman volume flux at the base of the Ekman layer has been computed. We have zonally integrated the meridional and vertical components across the world ocean and individual ocean basins, and present maps of the time-latitude variation of these transports. The contribution of the Pacific Ocean dominates the global zonal integrals in the extratropics. The Indian Ocean exhibits a large annual cycle in meridional Ekman volume flux. Ekman upwelling in the tropics of the Atlantic and Pacific occurs from June through November. The maximum upward vertical Ekman volume flux slightly exceeds 2.5 sverdrup in the Pacific and 1.0 sverdrup in the Atlantic and occurs centered around 10°N in each ocean.

1. Introduction

We have used monthly climatological estimates of wind stress over the world ocean prepared by Hellerman and Rosenstein (1983) to compute Ekman volume fluxes in the world ocean on a one-degree latitude–longitude grid. Both meridional and zonal Ekman volume fluxes have been computed and, from their divergence, the vertical Ekman volume flux at the base of the Ekman layer has been computed. We have zonally integrated the monthly estimates of meridional and vertical components over individual ocean basins as well as the world ocean and present time–latitude plots of these quantities.

One purpose of presenting these results is to make available a consistently computed set of estimates of Ekman volume fluxes for the world ocean. This allows for the comparison of the relative contribution of the Ekman flux in each ocean basin to the global integral of the Ekman flux. One often comes across estimates of various Ekman flux quantities in the literature, but these are often annual mean values for individual latitude belts. Variations in grid size or the domain over which these computations have been performed can make intercomparison of these estimates difficult. Hence the need for a consistent global set of estimates. To our knowledge there have been no previous comprehensive presentations of global and individual ocean basin estimates of these climatological fluxes for the annual cycle. Researchers should have easy access to these estimates and part of the purpose of our work is to provide this access. Our main purpose, however, is to obtain estimates of the role of Ekman dynamics in the general circulation of the ocean. In earlier work (Kraus and Levitus, 1986; Levitus, 1987), we have used estimates of Ekman volume fluxes to estimate meridional Ekman heat fluxes in the world ocean. Some of the earliest work on the computation of Ekman fluxes includes that of Fofonoff (1962) who presented maps of zonal and meridional Ekman volume flux for the North Pacific Ocean for January 1959.

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2. Computational procedures

Zonal and meridional Ekman volume fluxes are defined respectively as

$$Q_\lambda = \tau_\phi/f\rho = \int_{-h}^{0} U_E dz \qquad (1)$$

$$Q_\phi = -\tau_\lambda/f\rho = \int_{-h}^{0} V_E dz \qquad (2)$$

in which τ_λ, τ_ϕ are the zonal and meridional components of wind stress, ρ is the density of sea water, and f is the Coriolis parameter. The U_E and V_E are the Ekman velocity components and $-h$ is the depth of the Ekman boundary layer. The dimensions of the components of Q are cm^3/(cm-sec). We use the notation of Pond and Pickard (1978) in our work and one can refer to their work or the texts by Neumann and Pierson (1966), Stommel (1965), or Gill (1982) for derivations of these Ekman fluxes and/or discussions of Ekman layer dynamics. We have also computed the horizontal divergence of the Ekman volume transports in spherical coordinates defined as

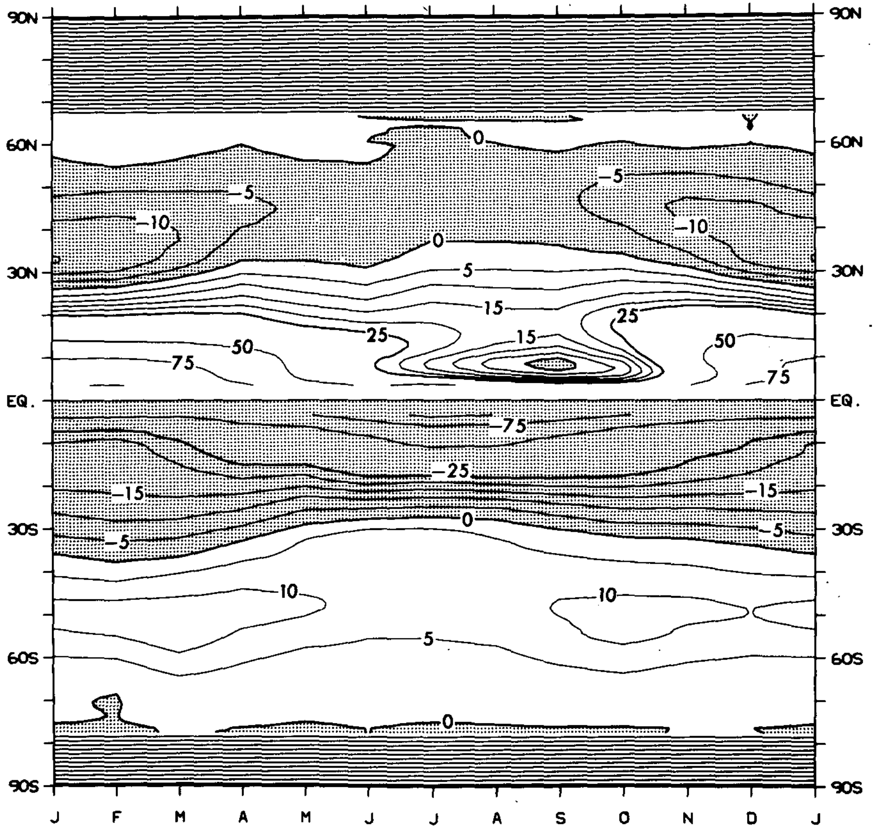

FIG. 1. Pacific Ocean zonally integrated meridional Ekman volume fluxes across one-degree latitude belts (10^6 m^3 s^{-1}) as a function of month and latitude. Shading indicates a negative flux (from north to south).

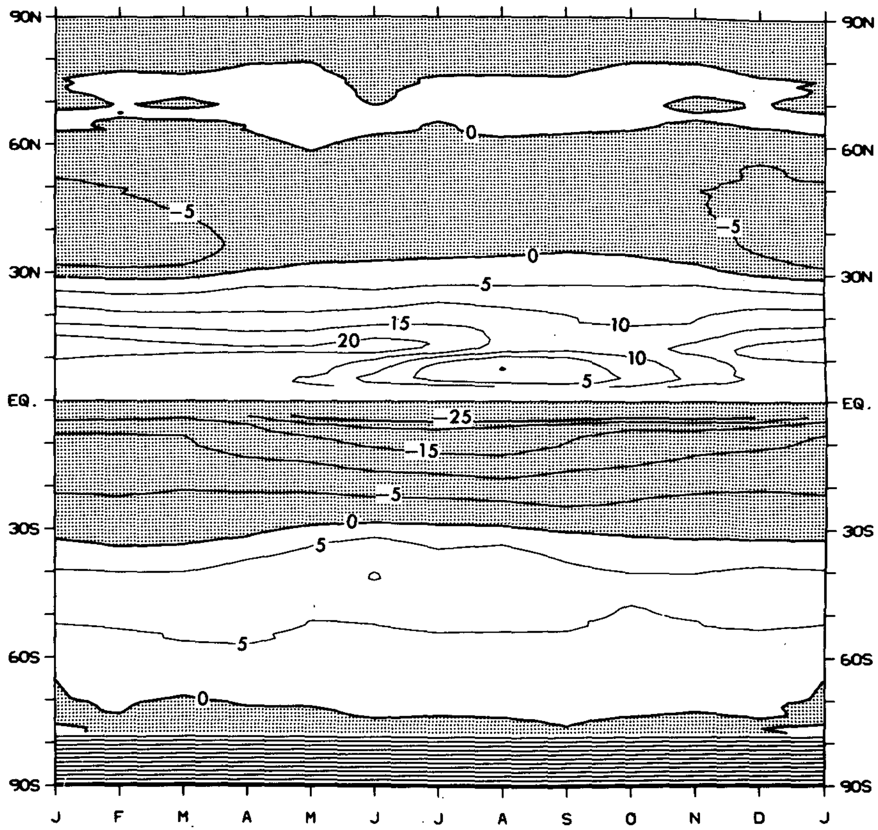

FIG. 2. As in Fig. 1, but for the Atlantic Ocean.

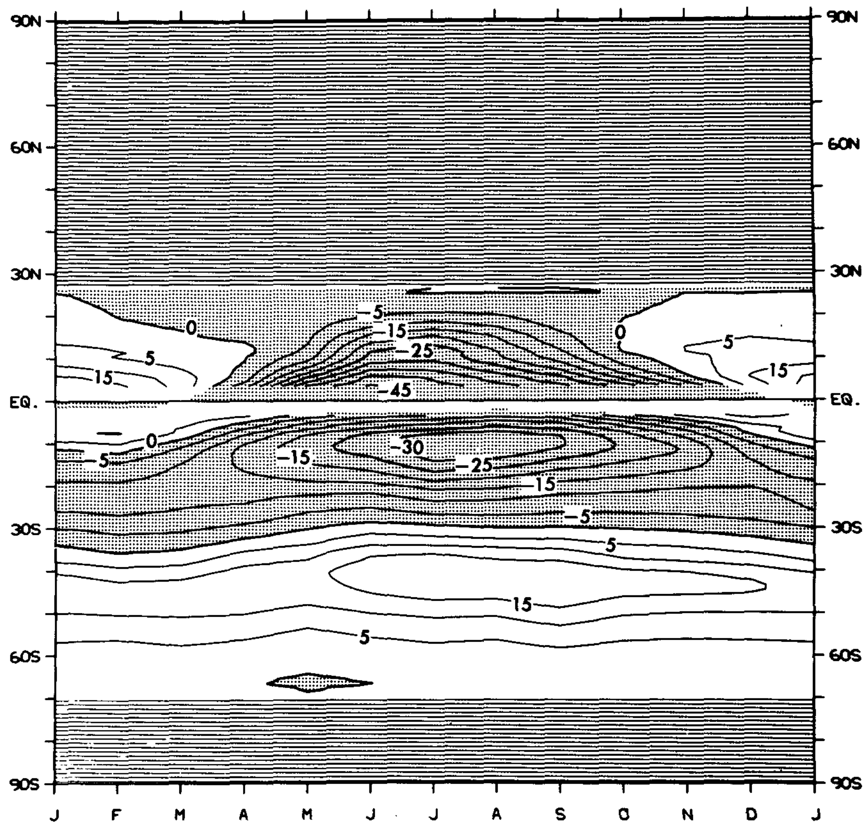

FIG. 3. As in Fig. 1, but for the Indian Ocean.

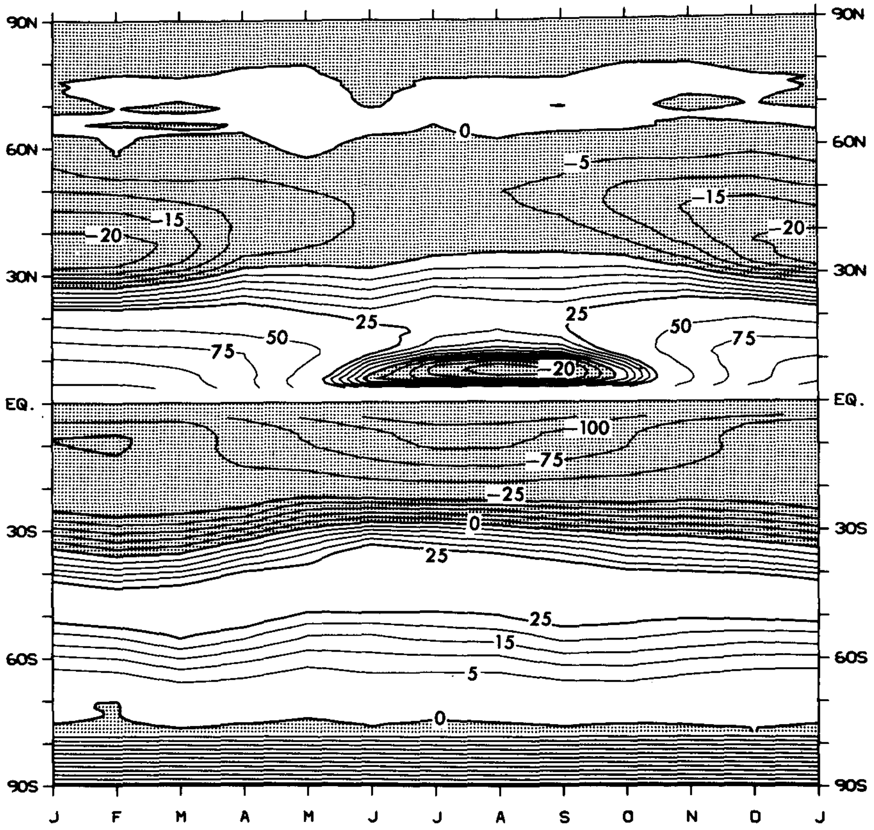

FIG. 4. As in Fig. 1, but for the world ocean.

$$\nabla\cdot\mathbf{Q}=\frac{1}{a\cos\phi}\left[\frac{\partial Q_\lambda}{\partial\lambda}+\frac{\partial(Q_\phi\cos\phi)}{\partial\phi}\right] \quad (3)$$

in which Q is the total horizontal Ekman volume transport, a is the earth's radius, ϕ is latitude, and λ is longitude. Using (1) and (2) we can then write (3) as

$$\nabla\cdot\mathbf{Q}=\mathbf{k}\cdot\nabla\times(\tau/\rho f). \quad (4)$$

The horizontal divergence of the Ekman transport is simply proportional to the curl of the wind stress. The dimensions of the horizontal divergence in Eqs. (3) and (4) are cm s^{-1}. To obtain the vertical Ekman volume flux at the base of the Ekman layer, we first vertically integrate the three-dimensional continuity equation using the Ekman velocity components. On the assumption that the vertical velocity is zero at the sea surface, then the vertical velocity at the base of the Ekman layer $W_E(-h)$ can be defined as

$$\frac{1}{a\cos\phi}\left[\frac{\partial Q_\lambda}{\partial\lambda}+\frac{\partial(Q_\phi\cos\phi)}{\partial\phi}\right]=W_E(-h). \quad (5)$$

Hellerman and Rosenstein (1983) presented distributions of $W_E(-h)$ for the world ocean for selected months and Leetma and Bunker (1978) presented the annual mean distribution of $W_E(-h)$ for the North Atlantic, along with seasonal minus annual mean distributions of this quantity. We have chosen to compute and present the vertical Ekman volume flux at the base of the Ekman layer for consistency with our horizontal volume fluxes. To compute this flux in each one-degree square, we simply multiply the Ekman vertical velocity by the area of the grid square. The resulting flux is that of a 1-cm thick layer of water.

We have zonally integrated the monthly estimates of each component over individual ocean basins, as well as the world ocean. We present these integrals in the form of time–latitude maps. In addition, we plot the zonal integrals of the annual mean fluxes of these components.

3. Results

We will discuss each of the flux components separately and, in addition, we will discuss the Pacific and Atlantic Ocean estimates jointly, because they are qualitatively similar. The contours on our plots extend to within 4.5° of the equator. At some latitude, as the equator is approached, the Ekman balance of forces is no longer valid and the estimates of Ekman fluxes meaningless. This is the reason for not presenting results close to the equator. The choice of 4.5° latitude as our boundary is arbitrary. It should be noted that at some latitudes the Ekman balance may be valid during some parts of the year, but not during other parts of the year. Other investigators have chosen similar limits; Leetma and Bunker (1978), for example, used the 5° parallel as a boundary for their Ekman computation. Wyrtki (1981) suggests that poleward of 4° his estimates of Ekman fluxes appear reasonable.

One procedure we have followed throughout our plots is to stipple regions of negative values at all latitudes. This stippling provides information on the sign of the wind stress components to provide information in the equatorial region.

a. Meridional Ekman volume fluxes

Figures 1–4 are the time–latitude plots of the zonally integrated meridional Ekman volume fluxes for the Pacific, Atlantic, Indian, and world oceans, respectively. Figure 5 is a plot of the zonally integrated annual mean meridional Ekman volume flux as a function of latitude for each basin.

1) PACIFIC AND ATLANTIC OCEANS

The annual cycle of meridional volume fluxes for the Pacific and Atlantic oceans are qualitatively alike, owing to the similarity of the overlying atmospheric circulations. The easterly winds of the tropics and subtropics are responsible for poleward volume flux in each hemisphere, from the equator to approximately 33° latitude in each ocean basin. The Ekman volume fluxes are larger in the Pacific than in the Atlantic and the annual range is larger also. For example, at 13°N a meridional volume flux of about 50 Sv (1 Sv $\equiv 10^6$ m^3 s^{-1}) occurs during November–April at 15°N in the Pacific, while in the Atlantic, a value of 20 Sv. occurs at this latitude during the same period. In fact, fluxes with magnitudes of 50 Sv simply do not occur in the Atlantic. The most interesting feature in each ocean occurs at about 8.5°N. A large annual cycle occurs at this latitude with maximum values occurring in January–March and with minimum values found in August–September when the confluence of the trade winds is farthest north. Distributions of climatological winds for Northern Hemisphere summer presented by Hastenrath and Lamb (1977) show the southeast trade winds crossing the equator and developing a westward component in regions of the tropical Atlantic and eastern Pacific Oceans. In the Pacific, westerly winds are responsible for a net southward flux in the zonal mean volume flux during September at 8.5°N.

2) INDIAN OCEAN

The Indian Ocean exhibits a distinct annual cycle at all latitudes. From 26°N to 33°S, there are large southward fluxes during April–October. Southward fluxes with magnitudes exceeding 25 Sv occur at 10° latitude in each hemisphere. A maximum southward flux of 45 Sv occurs at 4.5°N during June. In the 12° to 30°S latitude belt the fluxes are southward throughout the year. A maximum southward flux in excess of 30 Sv occurs from July through September. It is clear that both north and south of the equator the intense winds associated with the summer monsoon are responsible for substantial southward Ekman volume fluxes. Corresponding features do not occur during the winter monsoon. In the North Indian Ocean, positive fluxes occur at all latitudes during some part of the year.

3) WORLD OCEAN

The most prominent feature of the global meridional Ekman volume flux is the southward flux in excess of 20 Sv during July–September centered at 7.5°N. This southward flux is due to the contribution from the Indian Ocean.

4) ANNUAL MEAN MERIDIONAL EKMAN VOLUME FLUX

The annual mean meridional volume fluxes plotted in Fig. 5 show that the North Atlantic and North Pacific have northward fluxes in the 0°–30°N latitude belt. The Atlantic has a relative maximum at 12.5°N and the Pacific Ocean exhibits a plateau in its meridional profile at this same latitude. These two features are responsible for a relative maximum in the global profile at 12.5°N. Poleward of 30°N, the fluxes are equatorward in both oceans with the exception of some small poleward fluxes in polar and subpolar latitudes. The North Indian Ocean has a southward annual mean volume flux at all latitudes which is due to the strong summer monsoon southward flux. Between 4.5°S and 30°S, the Atlantic and Pacific Oceans exhibit a southward Ekman volume flux. The Indian Ocean has a southward flux from 3.5°S to 30°S with a maximum at 11°N. Poleward of 30°S, all three oceans exhibit a northward flux. The Indian and Atlantic Oceans exhibit a relative extreme at about 43°S, which lead to a maximum in the global flux at this latitude.

b. *Vertical Ekman volume fluxes*

Figures 6–9 are the time–latitude plots of the zonally integrated vertical Ekman volume flux at the base of the Ekman layer for the Pacific, Atlantic, Indian, and world oceans, respectively. Figure 10 displays the annual mean meridional profiles of these zonally integrated fluxes as a function of latitude for each ocean basin.

1) PACIFIC AND ATLANTIC OCEANS

The major features of the Pacific and Atlantic Oceans are the upward flux at high latitudes with magnitude not exceeding 2.5 Sv in any month. In lower latitudes, a downward flux occurs throughout most of the region with magnitudes slightly greater than 5.0 Sv occurring in the Pacific. In both oceans, upward fluxes occur during June–November in the Northern Hemisphere tropics centered on the 10°N latitude circle. Maximum values exceeding 2.5 and 1.0 Sv occur in the Pacific and Atlantic Oceans, respectively.

2) INDIAN OCEAN

In the Indian Ocean an upward flux occurs in the tropics and subtropics of both hemispheres in contrast to the Pacific and Atlantic Oceans. Between 4.5°N and 10°N, a semiannual component is observed in the annual cycle. A small downward flux occurs during July centered at about 8.5°N. Substantial upward fluxes occur in the tropics of each hemisphere; values exceeding 5.0 Sv occur in each hemisphere. The maximum up-

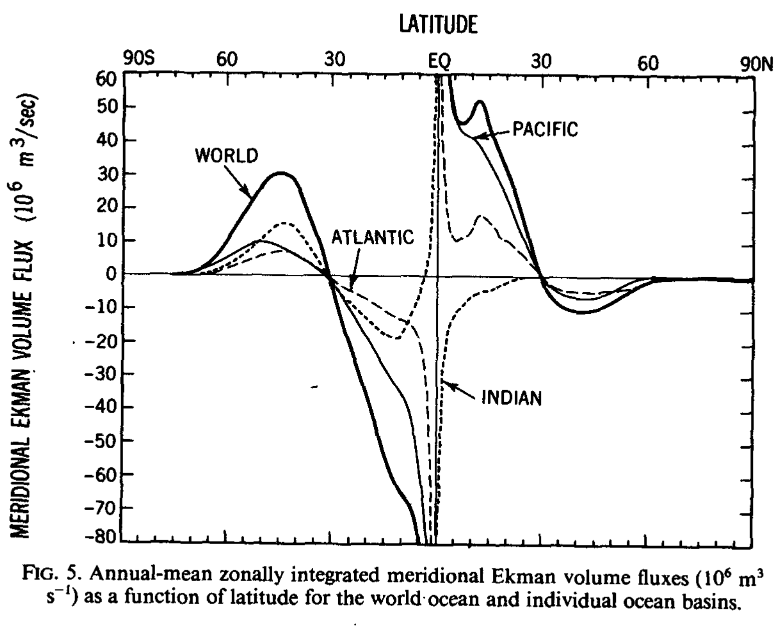

FIG. 5. Annual-mean zonally integrated meridional Ekman volume fluxes (10^6 m^3 s^{-1}) as a function of latitude for the world ocean and individual ocean basins.

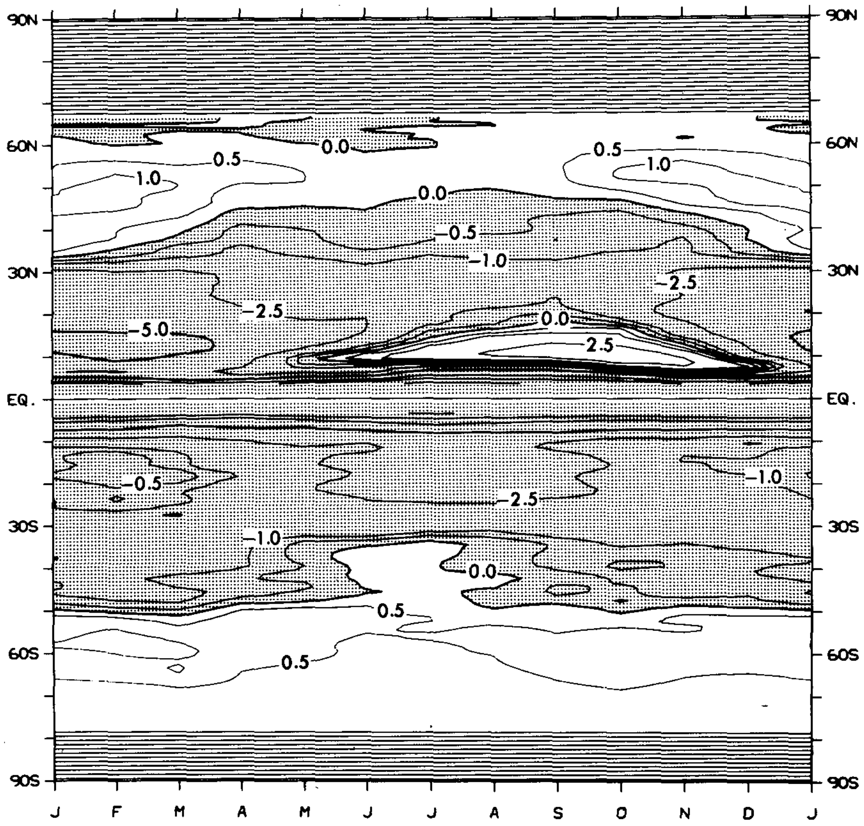

FIG. 6. Pacific Ocean zonally integrated vertical Ekman volume flux ($10^6\ m^3\ s^{-1}$) at the base of the Ekman layer per one-degree latitude belt as a function of month and latitude. Shading indicates a negative flux (downward).

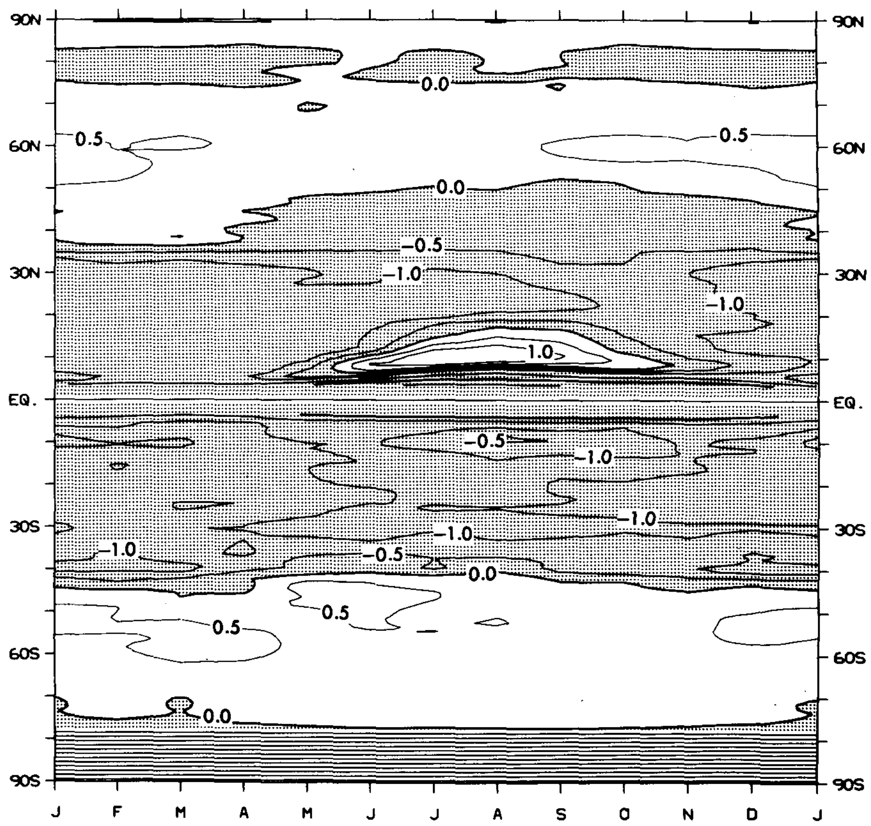

FIG. 7. As in Fig. 6, but for the Atlantic Ocean.

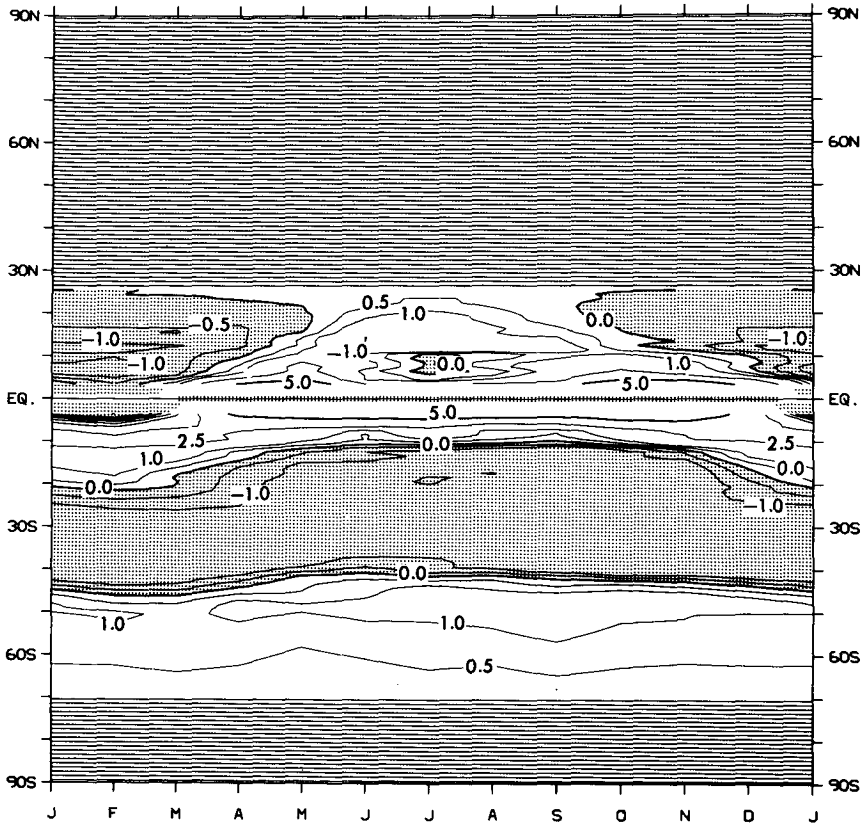

FIG. 8. As in Fig. 6, but for the Indian Ocean.

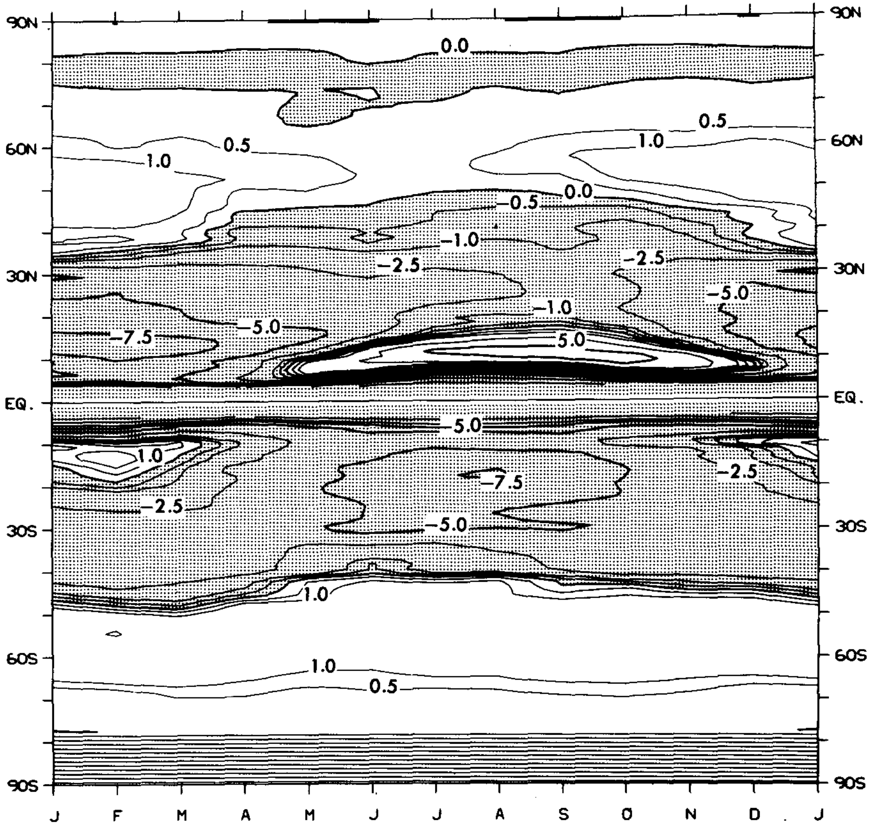

FIG. 9. As in Fig. 6, but for the world ocean.

ward flux occurs during April–May and October–November at 4.5°N.

3) World ocean

The global distribution of vertical Ekman volume fluxes exhibits prominent annual cycles in the tropics of each hemisphere. Upward (positive) fluxes occur during the summer in the tropics of each hemisphere due to contributions from all three oceans (with the exception of the previously noted Indian Ocean downwelling during July). The Southern Hemisphere Ekman upward flux is due entirely to the Indian Ocean contribution because no upward flux occurs in either of the other two oceans. Maxima exceeding 5.0 and 1.0 Sv occur in the tropics of the Northern Hemisphere and Southern Hemisphere, respectively. A negative Ekman flux with a magnitude exceeding 7.5 Sv occurs in the tropics and subtropics of the Northern Hemisphere, while negative fluxes with magnitudes exceeding 5.0 Sv occurs in the Southern Hemisphere tropics and subtropics. Upward fluxes in high latitudes slightly exceed 1.0 Sv in each hemisphere.

4) Annual mean vertical Ekman volume fluxes

Figure 10 displays the annual mean vertical Ekman volume flux for individual oceans, as well as the world ocean. Positive values of this flux occur at all latitudes of the Indian Ocean north of about 13°S, so upward Ekman fluxes occur in this basin on an annual mean basis. In the other ocean basins, the cyclonic regions of wind stress lead to positive Ekman fluxes at high latitudes while the anticyclonic regions at lower latitudes lead to negative Ekman fluxes.

4. Conclusions

We have presented climatological time–latitude distributions of zonal integrals of the meridional and vertical components of Ekman volume flux for individual ocean basins, as well as the world ocean. For each component, the major features of the Pacific and Atlantic are qualitatively alike owing to the similarities of the wind fields over each ocean. The zonally averaged zonal wind component over the Atlantic and Pacific is nearly symmetrical about the equator with easterly winds in the tropics and subtropics of each hemisphere, westerlies in midlatitudes, and easterlies in subpolar and polar latitudes. The easterly trade winds lead to poleward Ekman volume fluxes in each basin. The midlatitude westerlies are responsible for equatorward fluxes in each hemisphere. The Indian Ocean south of 10°S qualitatively resembles the South Atlantic and South Pacific, but the North Indian Ocean is different than its Northern Hemisphere counterparts. The monsoon circulation is responsible for a southward volume flux at nearly all latitudes during April–October and northward fluxes during November–February.

Vertical Ekman fluxes are positive (upward) in the tropics of the North Atlantic and North Pacific during Northern Hemisphere summer. A semiannual cycle is present in the tropics of the North Indian Ocean. In the tropics of the South Indian Ocean, fluxes are positive during Northern Hemisphere winter.

As a final note, we wish to emphasize that the Ekman fluxes described in this paper represent a single com-

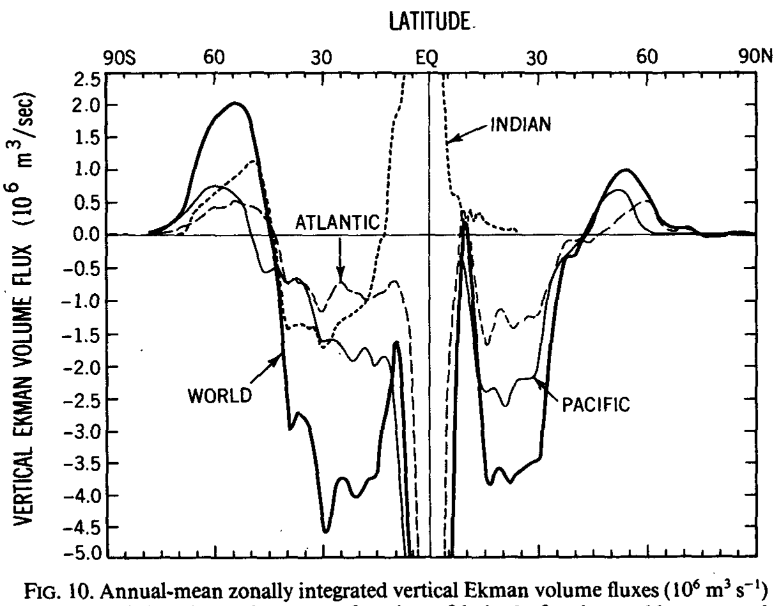

FIG. 10. Annual-mean zonally integrated vertical Ekman volume fluxes (10^6 m^3 s^{-1}) at the base of the Ekman layer as a function of latitude for the world ocean and individual ocean basins.

ponent of the ocean circulation and must be interpreted as such.

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